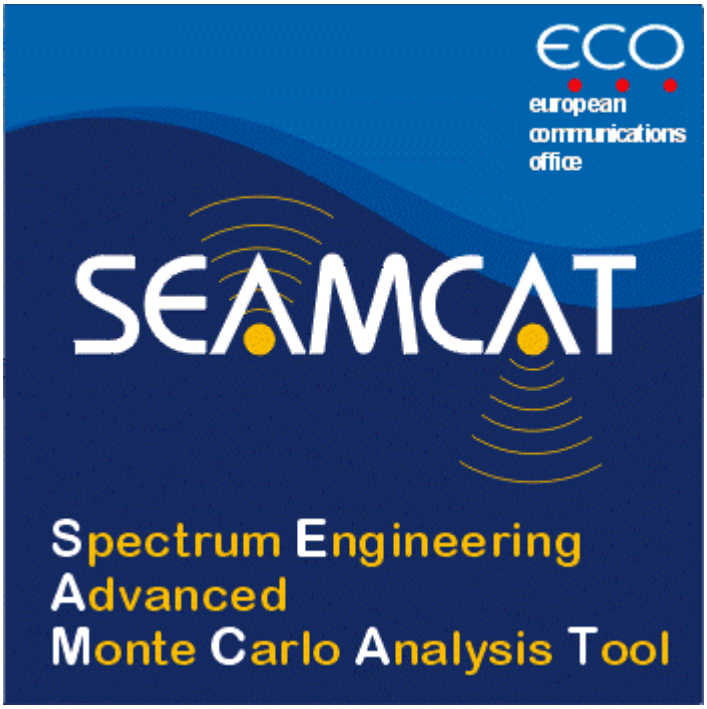

Manual on Cognitive Radio Simulation

July 2010

ECO
european
communications
office

About the CEPT and ECO

The European Conference of Postal and Telecommunications Administrations (CEPT) is an organisation where policy makers and regulators from 48 countries across Europe collaborate to harmonise telecommunication, radio spectrum and postal regulations.

The European Communications Office (ECO) is the Secretariat of the CEPT. It provides advice and support to CEPT to help it to develop and deliver its policies and decisions in an effective and transparent way. Its core duties are to provide a European centre of expertise in electronic communications, to contribute to the work of the three CEPT committees and to manage CEPT's day-to-day activities.

ECO further supports CEPT member countries and other stakeholders providing a forum to debate and advance European communications policy for the benefit of all Europe's citizens.

Acknowldegment

ECO would like to thank many participating companies and organisations to the SEAMCAT MoU, who made the creation of SEAMCAT tool possible. Special thanks go to the active members of **CEPT Working Group Spectrum Engineering (WG SE)**, **SEAMCAT Management Committee (SMC)** (1997-2002), and **SEAMCAT Technical Group (STG)** (since 2003), whose many contributions formed the main basis of the work in the SEAMCAT project in general and the content of this document in particular.

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Section 1

Introduction

ECO (European Communications Office) is responsible for the software software tool, named SEAMCAT (Spectrum Engineering Advanced Monte Carlo Analysis Tool), which is based on the Monte-Carlo simulation method, to enable statistical modelling of different radio interference situations. It has been developed to deal with a complex range of spectrum engineering and radio compatibility problems.

Cognitive radio is a new technology which is being developed to bring greater efficiency, speed and reliability to users of wireless devices. The number of high powered wireless devices coming on to the market is increasing exponentially placing an unprecedented demand on the limited radio spectrum. Cognitive radio technology is seen as a potential solution to this problem as it identifies unused frequencies in a local area and switches a device to this temporarily to provide users with uninterrupted and faster mobile services.

The **Manual on Cognitive Radio Simulation** has been developed to aid technical studies into this new technology. The manual sets out how SEAMCAT can be used for spectrum sensing where the interfering devices (It) try to detect the presence of protected services (e.g. the Wt) transmitting in each of the potentially available channels.

Spectrum sensing essentially involves conducting a measurement within a candidate channel to determine whether any protected service is present and transmitting. When a channel is determined to be vacant, sensing is typically applied to adjacent channels to identify what constraints there might be on transmission power, if any.

A key parameter for spectrum sensing is the detection threshold that is used by a cognitive device to detect the presence or the absence of a protected service's transmission. If it detects no emission above this threshold in a channel, the white space device (WSD, i.e. the It) is allowed to transmit, otherwise the WSD keeps silent or look into other channels.

SEAMCAT allows studying this phenomenon with its implementation of the algorithm in Annex 4. SEAMCAT enables multiple cognitive radio systems. The cognitive radio feature mainly introduces the detection threshold and the selection of the operating frequency of the WSD.

ECO maintains an online SEAMCAT user manual at http://seamcat.iprojects.dk/wiki/Manual. Users are encouraged to go to this link to get the latest information on the software and to access free downloadable software and reference sources.

Section 2

The Cognitive Radio scenario

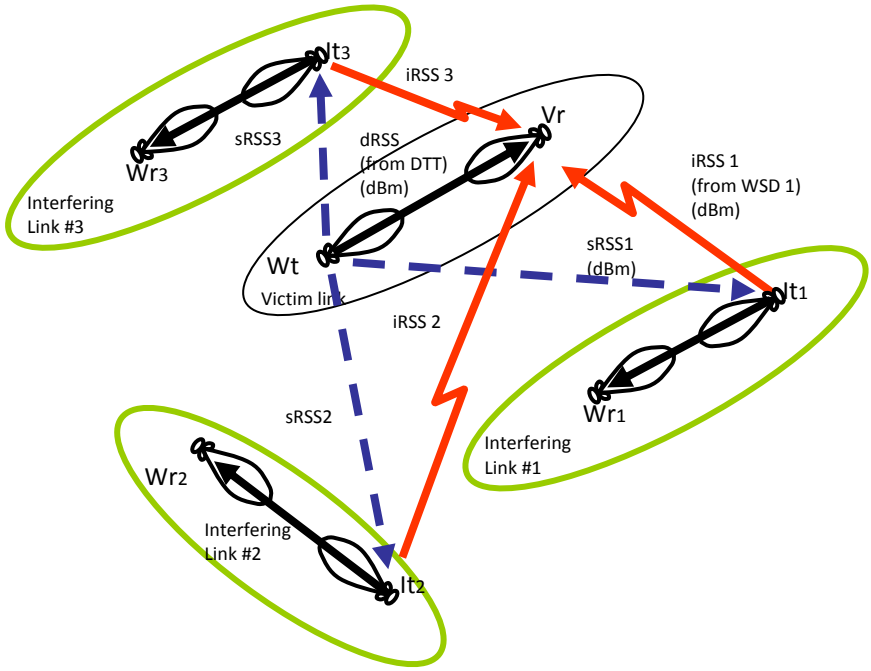


Figure 1: Illustration of 3 cognitive radio systems (WSD) and a victim system

In [1]SEAMCAT, the interference scenario considers 3 different received signals. These signals are illustrated in Figure 1 and defined as follows:

- **dRSS (desired Received Signal Strength)** represents the signal transmitted by the Wanted Transmitter (Wt) to the Victim Receiver (Vr). This is the signal which will experience impairment due to the interferer. For instance it may be a DTT (Digital Terrestrial Television) system.
- **iRSS (interfering Received Signal Strength)** represents the signal transmitted by the Interfering Transmitter (It) and received by the Victim Receiver (Vr). This is the signal which will impair the dRSS. Here, the It acts as a transmitting device.
- **sRSS (sensing Received Signal Strength)** represents the signal which is transmitted by the Wt and is sensed by the It. Note that the It acts as a transceiver, meaning that when the energy is sensed though the bandwidth of the sensing device (i.e. the It), it is acting as a receiving device.

[1] The current tree-folder (ver. 3.2.1) will be removed in future versions of SEAMCAT, and users are not advised to use it since 'scenario' and 'control' are obsolete to set-up the simulation. Instead users are encouraged to set-up their simulation using the **workspace menu bar**. Users can still use the tree-folder 'Results' to extract vector results. The graphics are based on SEAMCAT version 3.2.1 unless otherwise mentioned.

The dRSS and the iRSS descriptions are provided in the SEAMCAT Handbook. The sRSS (considering the unwanted mask of the DTT) at the channel *m* is calculated as follows (See Annex 4):

$$sRSS(f_m) = P_{Wt}(f_m) + G_{Wt\rightarrow It} + G_{It\rightarrow Wt} + L$$

where :

- P_{Wt}: is the transmit power in dBm from the Wt.
- f_m : is the frequency of the WSD.
- $G_{Wt\rightarrow It}$: is the antenna gain in dBi of the Wt, in the Wt to It direction
- $G_{It\rightarrow Wt}$: is the antenna gain in dBi of the It in the It to Wt direction
- L: is the path loss in dB between the It and the Wt.

Section 3

How to simulate Cognitive Radio devices in SEAMCAT

In SEAMCAT, the CR device(s) is/are assumed to be the interferers. A SEAMCAT workspace will contain only 1 victim system and 1 or many interferers. It is possible to assess the aggregated impact of interferers that can be either CR devices or not. The scenario allows the impact of spectrum sensing to be investigated where a cognitive radio device is activated nearby a victim system.

Both the victim and the interfering dialogue interface should be filled to enable spectrum sensing in SEAMCAT.

3.1 Victim link

It is assumed that the frequency of the interfering cognitive radio device is dependent on the frequency range defined for the victim. This means that when the CR module is activated, the interfering frequency function dialogue box is de-activated. Depending on how the victim frequency is defined (i.e. constant, discrete or distributed between f_{min} and f_{max}). SEAMCAT only allows the use of the following distribution: Constant, User defined, Uniform, User defined (stair). See Annex 1 on how to define the frequency range of the victim device.

SEAMCAT automatically calculates the number of possible channels the WSD will operate in based on the operating frequency range of the victim system and its victim receiver bandwidth (see Figure 2).

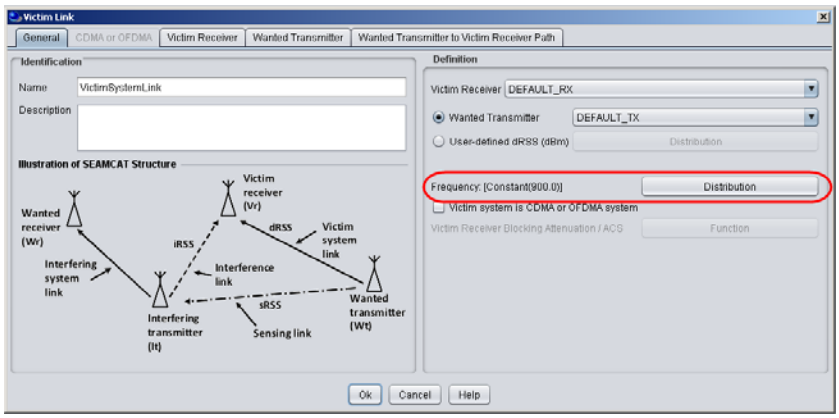


Figure 2: Setting the victim frequency

Then the user has to select the transmitting characteristic of the wanted transmitter, i.e. the energy that the cognitive radio spectrum sensing device is to sense, and the **use CR features** button to enable the emission mask and the emission floor.

Note that the settings of the emissions mask and the emission floor is the same as for the interfering link (i.e. same units). The emission floor is described in the SEAMCAT handbook on page 136.

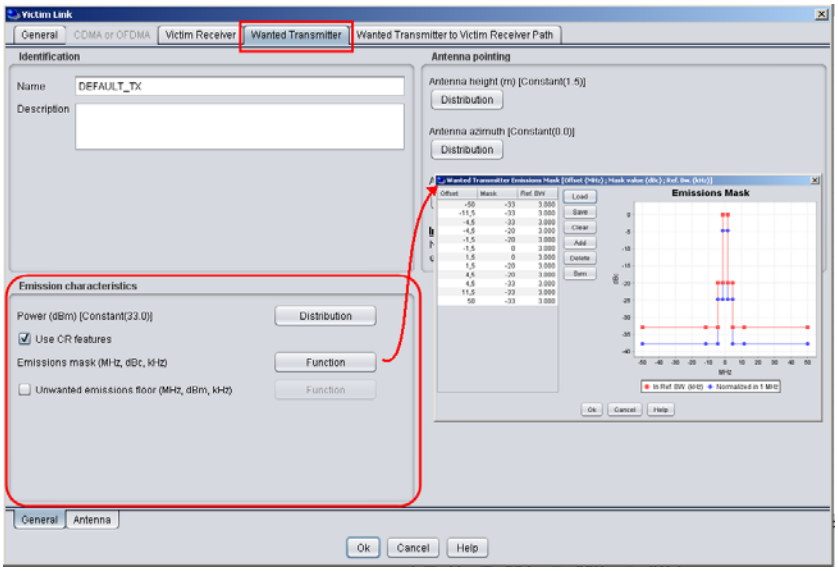
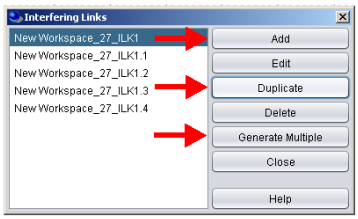


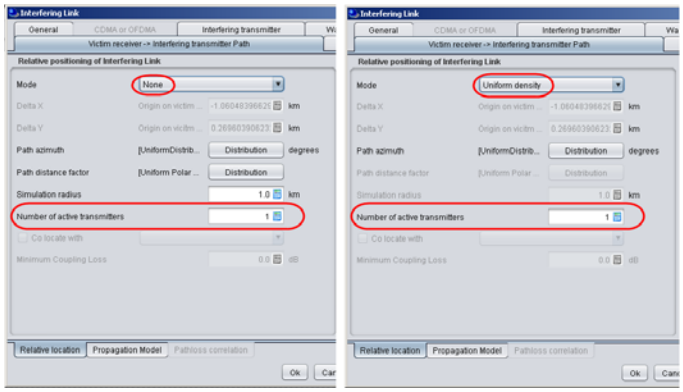
Figure 3: Activate the CR in the Wt (Victim Link) to consider its emission characteristics (i.e. used in the sRSS calculation)

3.2 Interfering link

As mentioned earlier, it is possible to simulate more than one interferer. The Number of cognitive radio device (WSDs) to simulate is user selectable. It can be set either by selecting numerous interfering link (i.e. add/duplicate/generate multiple) Figure 4 (a), by setting the number of active users (in ***none***, and ***uniform density*** mode only) Figure 4 (b) or a combination of the two.



(a) Numerous interfering links



(b) Setting a number of active transmitters (***none*** and ***uniform density*** mode) per interfering links

Figure 4: How to set more than one CR interferers

The interferers are selected as a cognitive radio device from the general dialogue box of the interfering link as shown in Figure 5. When the button **interferer is cognitive radio** is selected the following occurs:

- The selection of the frequency is disabled.
- The "OFDMA/CDMA" component is also disabled which means that the cognitive radio interferer can not be neither CDMA nor OFDMA.
- The wanted transmitter → interfering transmitter path is activated

Note that it is not possible to simulate "OFDMA/CDMA" as a victim and have a CR interferer. The implementation only considers traditional versus traditional. A consistency check will appears if the victim is CDMA/OFDMA and one of the interferer has the CR enabled (see Annex 6 for details).

Furthermore, the CDMA/OFDMA module in the interfering link window dialogue is disabled when the CR feature is activated.

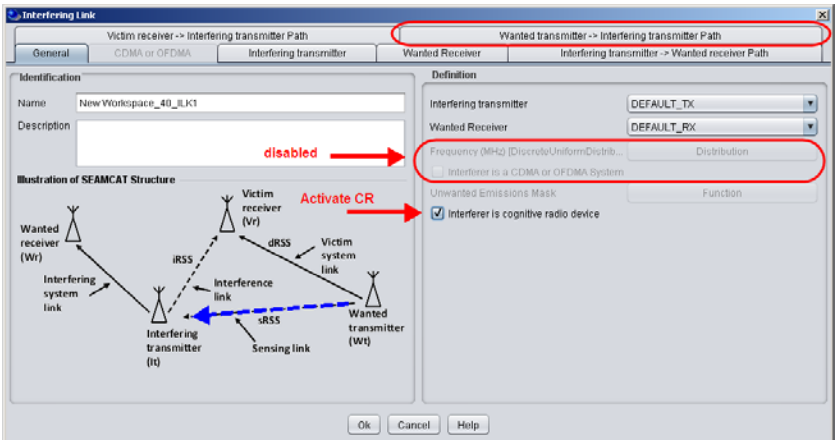


Figure 5: Selection of the CR feature in the Interfering Link

When an interferer is set as a CR, the emission characteristics (i.e. transmitted power, emission mask and unwanted emission mask) have to be entered as usual. In relation to the spectrum sensing results, if this CR detect that a victim system is in the vicinity it will select an appropriate operating frequency and it will lower its emission based on an E.I.R.P.max in block limit defined in the spectrum sensing characteristics (see Figure 6 and Figure 15 as output vector).

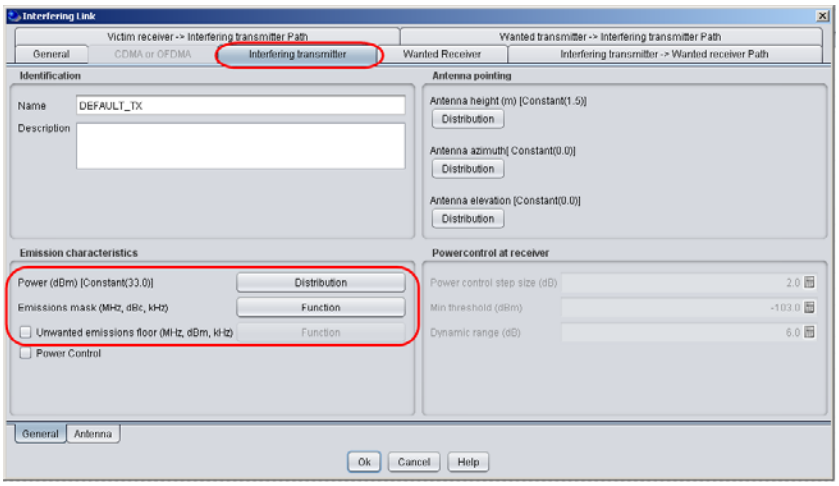


Figure 6: Setting the power and emission characteristics of the interfering WSD.

When an interferer is set as a CR, the spectrum sensing characteristics presented in Figure 7 have to be entered.

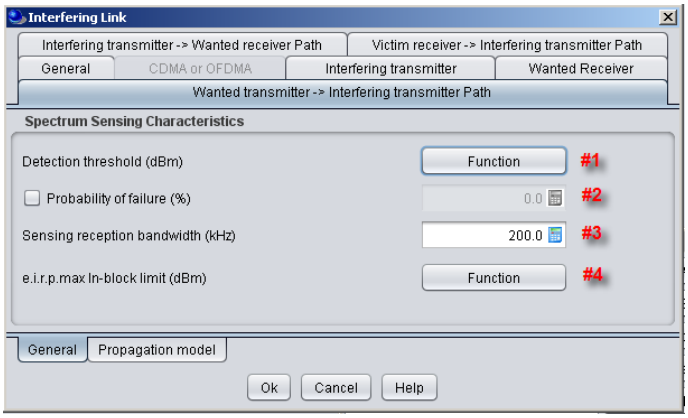
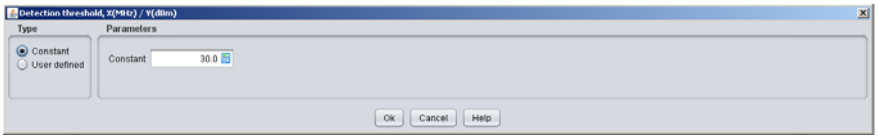
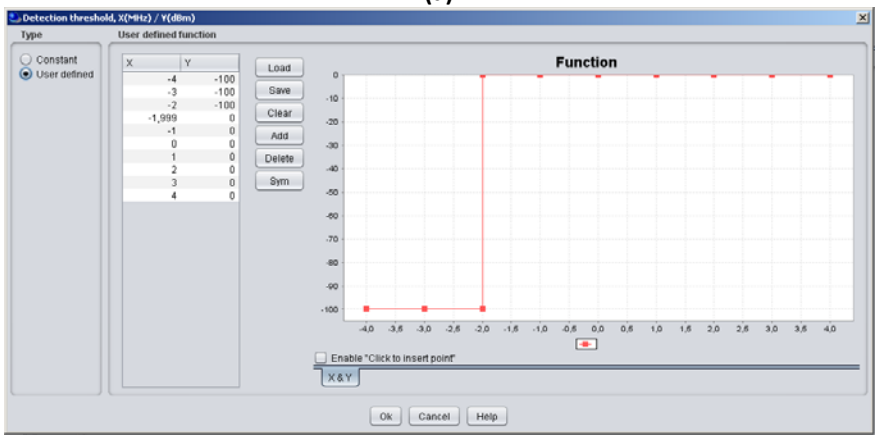


Figure 7: Setting the spectrum sensing characteristics in the Wanted Transmitter to Interfering Transmitter Path

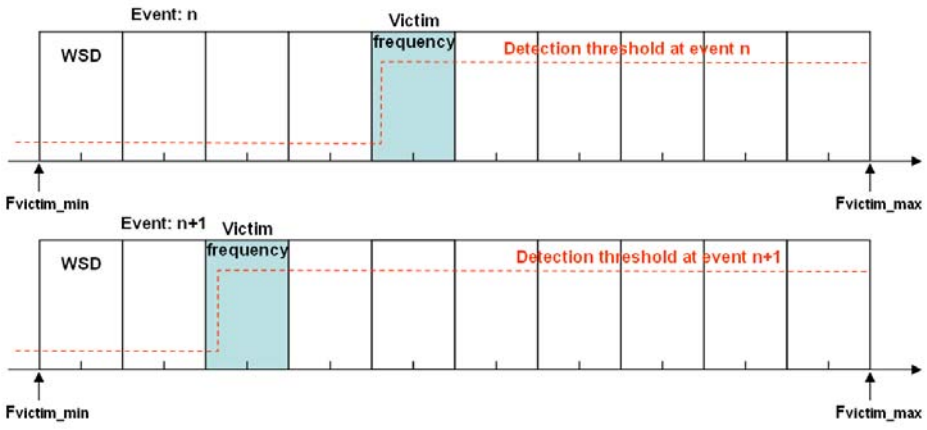
- Detection threshold (in dBm) : Either a constant value (i.e. flat over the spectrum) or as a user defined function as shown in #1 of Figure 7 illustrates the setting of the detection threshold (a) as a constant or (b) as a function. Figure 8 (c) illustrates where the offset refers to. Note the user defined function is defined as offset with the victim frequency being the reference.



(a)



(b)



(c)

Figure 8: Example of the detection threshold (a) as a constant or (b) as a function and illustrates in (c) where the offset refers to

- Probability of spectrum sensing failure (%): This function is selectable by the user as shown in **#2** of Figure 7. The probability of failure is given in percentage. In the illustration below a probability of failure of 10 % is entered.

- Define the bandwidth of the sensing device (i.e. It) (in kHz): This is a constant value given in kHz as shown in **#3** of Figure 7.

- E.I.R.P. *in-block* mask : SEAMCAT inputs the In-block CR emission limit as a triplet [offset, Mask, Ref.BW] where Offset in MHz is equivalent to the "DTT in use at" columns, Mask in dBm is the "In-block CR $EIRP_{max}$ limit" and Ref. BW is the bandwidth of the DTT as shown in **#4** of Figure 7. Note that SEAMCAT will normalise any value entered in the table to 1 MHz and convert back to the victim bandwidth.

In the example below a victim bandwidth (i.e. bandwidth of the DTT) of 8 MHz is illustrated.

DTT in use at	**In-block CR $E.I.R.P._{max}$ limit (dBm)**
co-channel	$-\infty$ = -1000
$n \pm 1$	-12.8
$n \pm 2$	3.2
$n \pm 3$	11.2
$n \pm 4$	16.2
$n \pm 5$	20.2
$n - 6$	16.2
$n + 6$	21.2
$n \pm 7$	22.2
$n \pm 8$	23.2
$n - 9$	4.2
$n + 9$	23.2
$n \pm 10$	24.2
$> n \pm 11$	25.2

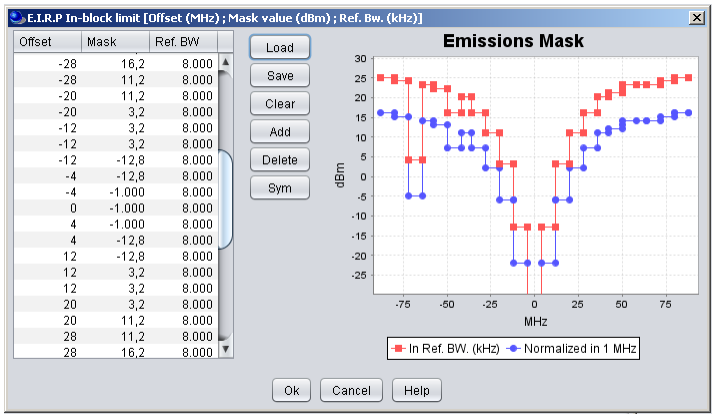


Figure 9: Example of setting the E.I.R.P. in-block mask

Section 4

How to read the output vectors

At the end of the simulation, SEAMCAT provides a set of output vectors as illustrated below:

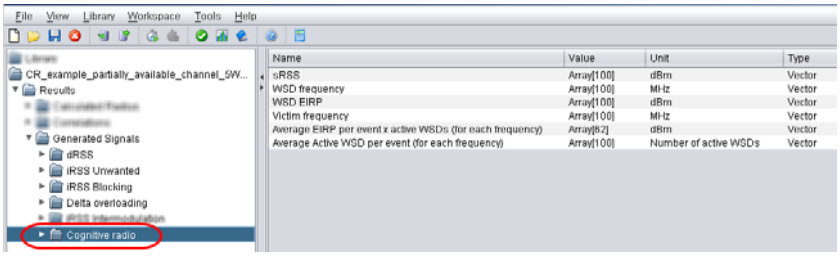


Figure 10: Set of output vectors when running CR simulation

Then the user can perform the interference probability calculation as described in the SEAMCAT handbook using the Interference Calculation Engine (ICE).

4.1 sRSS vector (dBm)

The sRSS vector is merely the sRSS value calculated at the selected WSD frequency (i.e. where the WSD is allowed to transmit) for each of the event. The sRSS is calculated according to the equation (1) of Annex 4. Figure 11 displays the vector for each WSD. The user can select any or all of the WSD (**#1**). The same applies to the CDF and density graphs (**#2**).

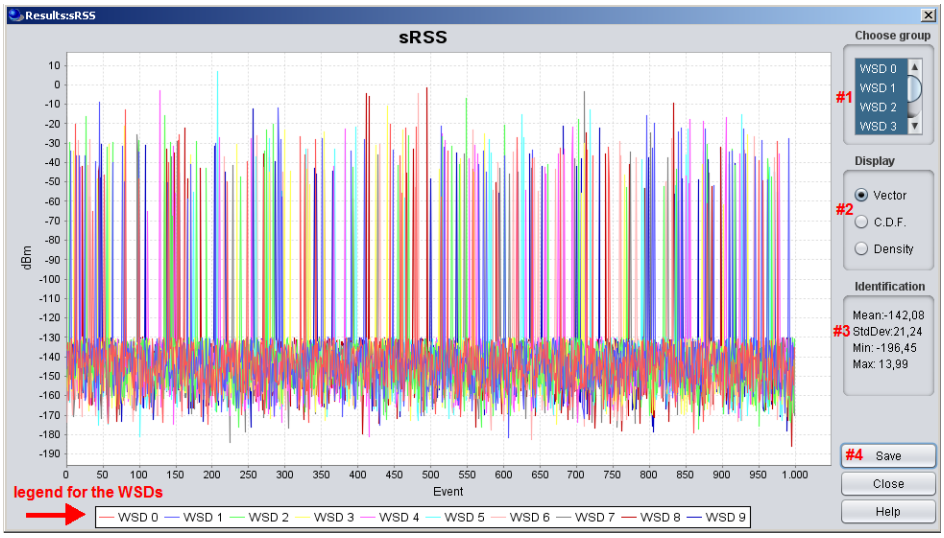


Figure 11: sRSS vector output

The user is able to save the results (**#4**) as .txt file for further post-processing.

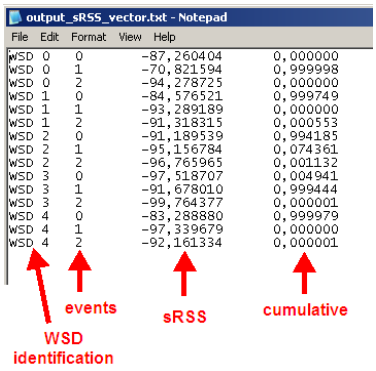
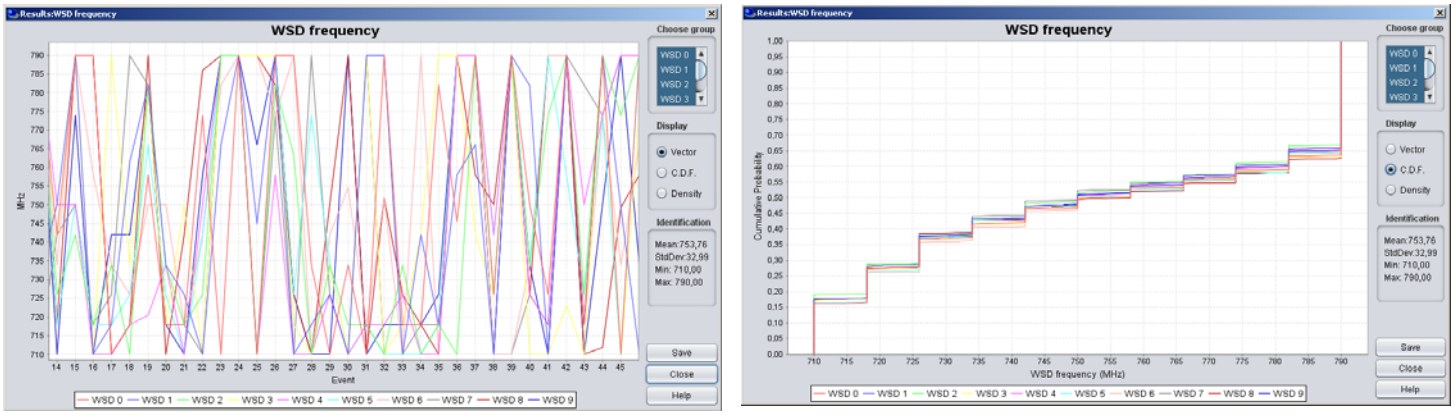


Figure 12: Saving format of the sRSS vector for post-processing

4.2 WSD frequency (MHz)

This vector represents the actual selected frequency at which the WSDs are allowed to transmit as the result of the spectrum sensing algorithm.



(a) **(b)**

Figure 13: Frequencies where the WSDs are transmitting as (a) vector display and (b) CDF

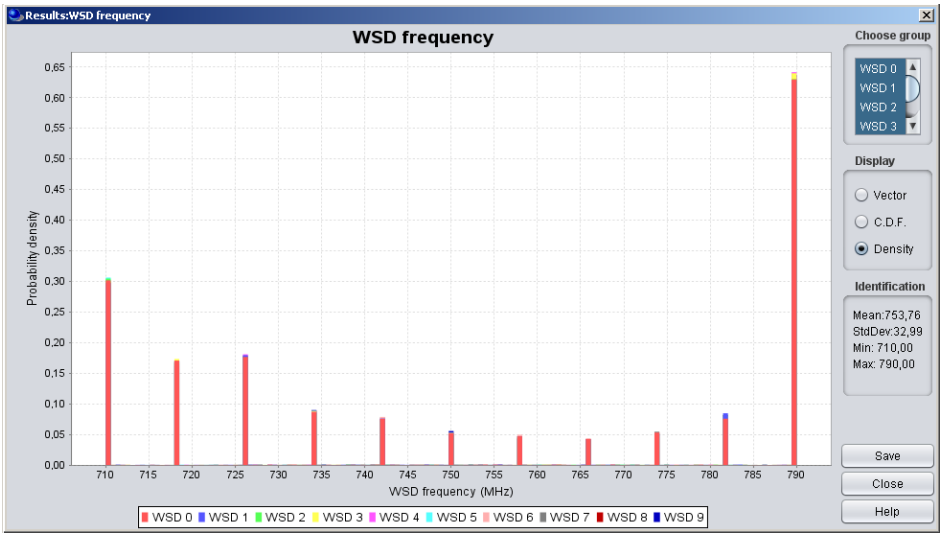


Figure 14: Density of the frequencies used by the WSDs.

4.3 WSD E.I.R.P. (dBm)

The actual selected E.I.R.P. at which the WSDs are allowed to transmit as the result of the spectrum sensing algorithm. This vector displays the E.I.R.P. for each of the WSD for all the events. In the example presented in Figure 15, the WSDs are transmitting with a E.I.R.P. between -10 and 20 dBm and -1000 dBm (equivalent to WSD switch off).

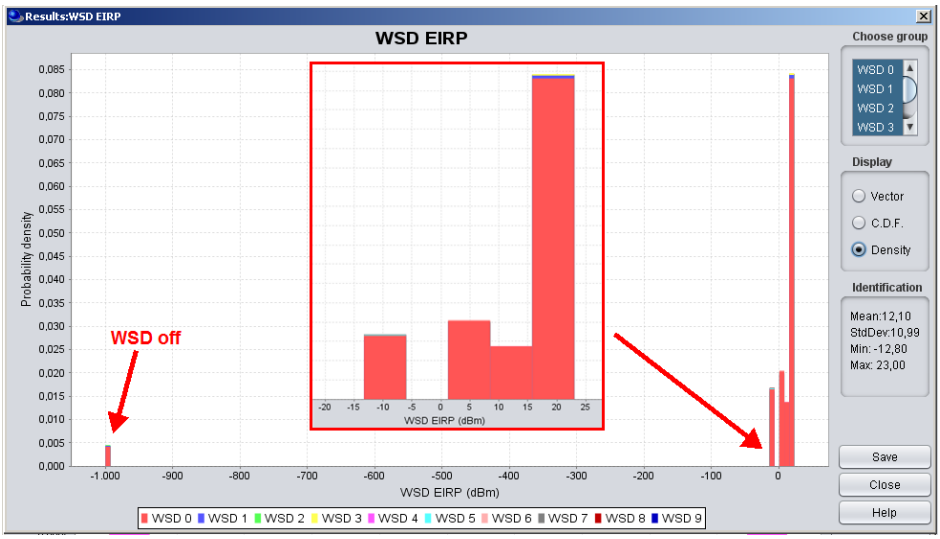


Figure 15: Example of the density of the E.I.R.P. per WSD

4.4 Victim frequency vector (MHz)

The victim frequency vector represents the frequency at which the victim device transmits per event. Figure 16 displays the CDF of the victim frequency and it depicts that the victim is placed at 1000.1, 1000.3, 1000.5, 1000.7 and 1000.9 MHz for this given example.

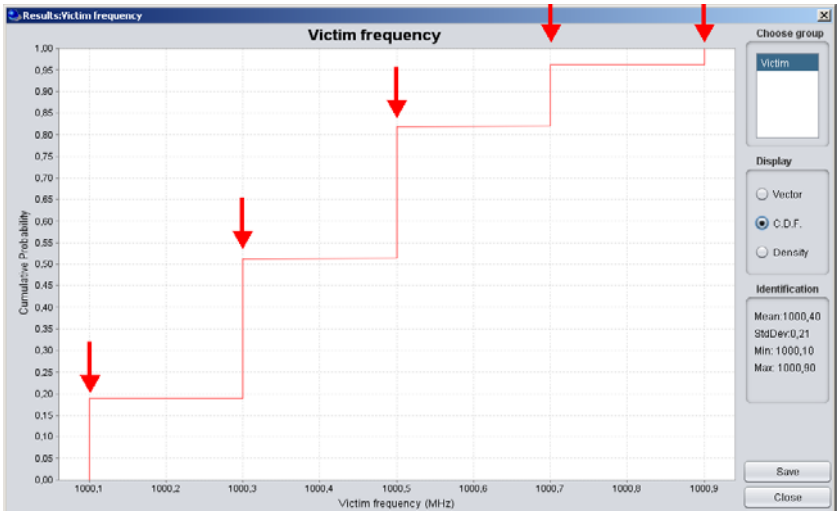


Figure 16: Example of the victim frequency

4.5 Average E.I.R.P. per frequency (dBm vs MHz)

It presents the average E.I.R.P. per event for all the active WSDs transmitting at a certain frequency such that:

$$AvgEIRP_{f_j} = 10 \times \log_{10}\left[\frac{1}{N_{activeWSD} \times N_{events}} \sum_{i=1}^{N_{activeWSD} \times N_{events}} 10^{\frac{EIRP_i}{10}}\right]_{f_j}$$

Let us assume a different example from above, where 4 channels have been identified for the WSD to operate. Figure 17 shows that on average 33 dBm, for one event, was transmitted by the active WSDs at 1000.5 MHz , 8.82 dBm at 1001.5 MHz etc...

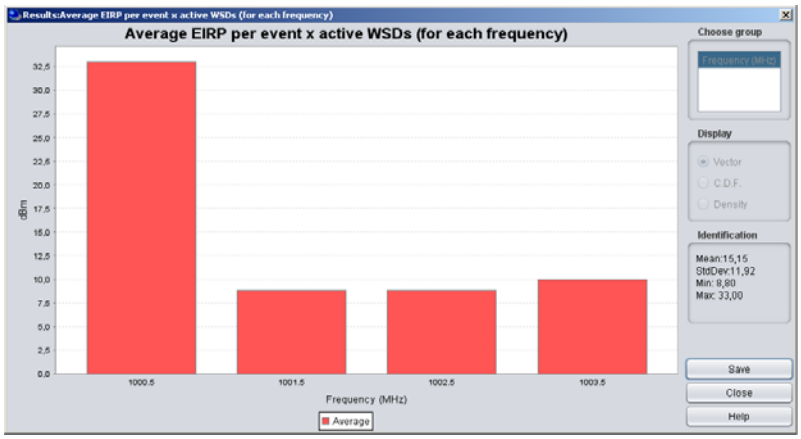


Figure 17: Average E.I.R.P. per frequency

4.6 Average active WSDs per frequency vector

It provides the average number of active WSD per event for a specific frequency:

$$NactiveWSD_{f_j} = \left[\frac{1}{N_{events}} \sum_{i=1}^{N_{events}} activeWSD_i\right]_{f_j}$$

Re-using the example of Figure 17, Figure 18 indicates that, with for instance 5 WSDs set as input parameters, an average of 0.63 WSDs were active at 1000.5 MHz (with 33 dBm E.I.R.P.- Figure 17), 1.29 WSDs were active at 1001.5 MHz (with 8.82 dBm E.I.R.P. - Figure 17), 1.57 active WSDs at 1002.5 MHz and 1.51 active WSDs at 1003.5 MHz. It can also be noted that in this particular example, the sum of the active WSDs across the selected frequencies is 5, meaning that all the simulated WSDs have been active and none have been turn off.

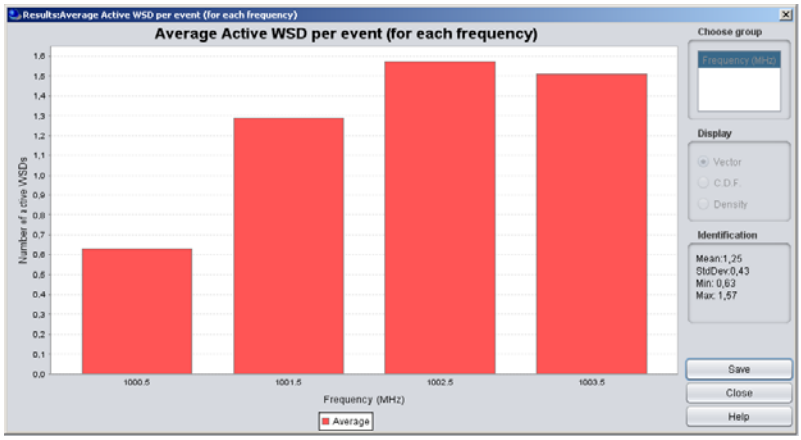


Figure 18: Average active WSDs per frequency

Section 5

Examples

5.1 All the channels are available

Scenario: test_CR_all_availabl e_channel.sws

In such a scenario, the detection threshold is taken to a value of 0 dB (Figure 19) much higher than the sRSS level (average = -82.09 dBm) (Figure 20). Therefore, no victim system has been detected and the WSDs are allowed to transmit in any of the specified channels (Figure 21) per event.

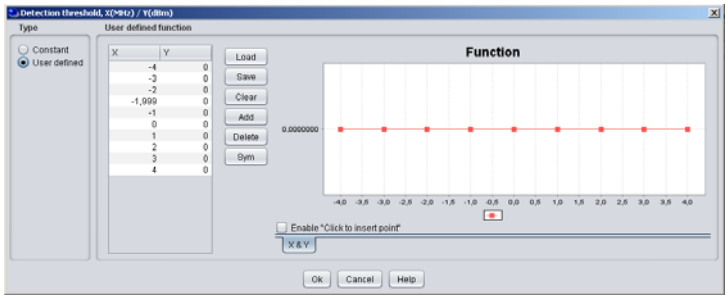


Figure 19: Selection of a high detection threshold

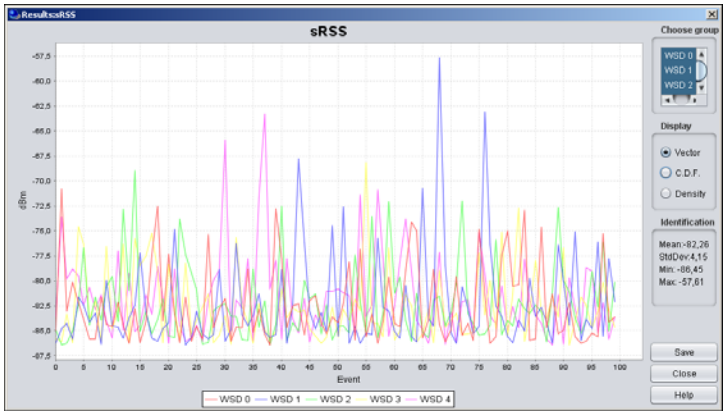


Figure 20: The sRSS values are well below the detection threshold, so no victim system have been detected.

In such a case the E.I.R.P. used in the simulation is the Tx_{power} (=-33 dBm) + G_{max} (=0 dBi), meaning that the in-block E.I.R.P. limit does not apply. This means that whatever the frequency selected by the WSD its E.I.R.P. is the same (Figure 23) (here assuming that the Power Control at the It is OFF).

Figure 21: The WSD can transmit anywhere in the victim frequency range.

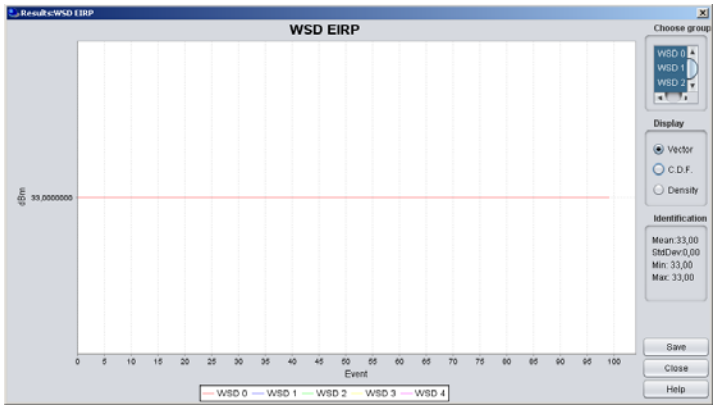


Figure 22: E.I.R.P. set to -33 dBm as set in the It, i.e. Tx_{power} (=-33 dBm) + G_{max} (=0 dBi), meaning that there were no limit applied to the It Tx power.

Figure 24 illustrates that on average there are 1.17 WSDs active at 1000.5 MHz per event, 1.23 WSDs in 1001.5 MHz, 1.34 WSDs in 1002.5 MHz and 1.26 WSDs in 1003.5 MHz for the same out of 5 which were input to the simulation. In this case all the WSDs were active (but in different frequencies) since the sum equal to 5 (i.e. none of the WSDs have been turned off).

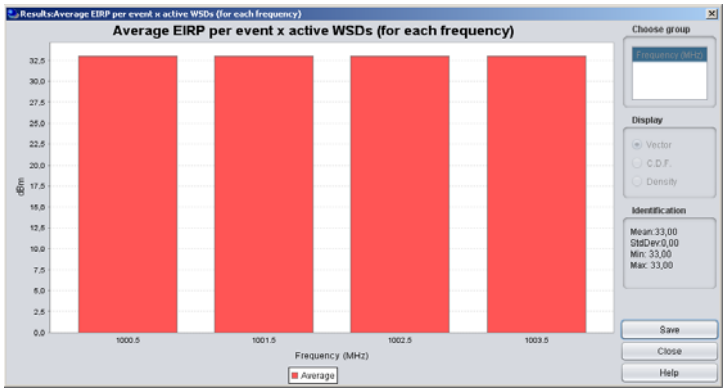


Figure 23: E.I.R.P. is the same irrespective of the frequency

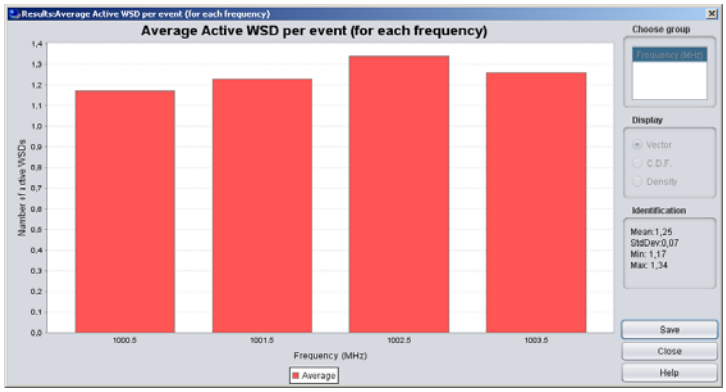


Figure 24: illustration of the number of WSDs per frequency

5.2 All the channels are blocked

Scenario: test_CR_all_blocked_channel.sws

In such a scenario, the detection threshold is taken to a lower value compared to the sRSS and none of the WSDs are transmitting. In SEAMCAT, the Tx power is set to -1000 dBm (Figure 25). The WSD frequency is the same as the victim frequency per event.

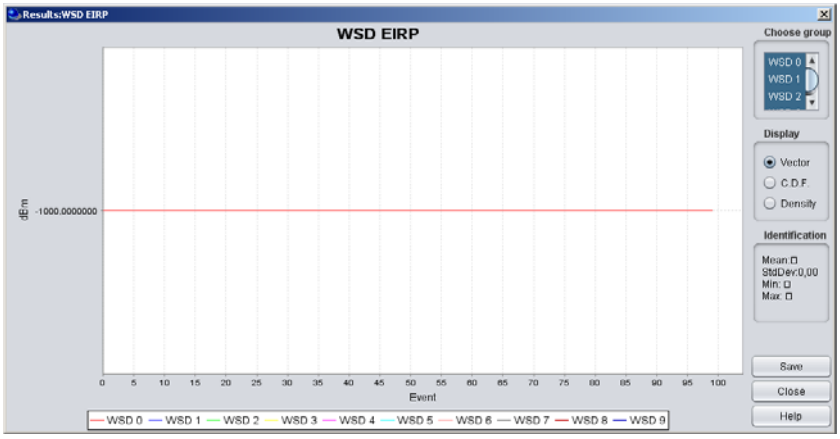


Figure 25: all the WSDs are off i.e. -1000 dBm

Note that in this specific case, the average E.I.R.P. and average WSDs per frequency can not be calculated and therefore can not be displayed as shown in Figure 27.

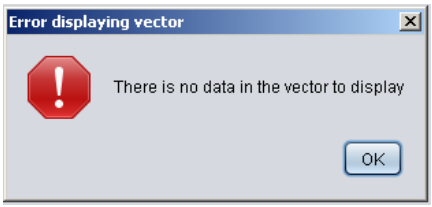


Figure 26: all the WSDs are off i.e. -1000 dBm

5.3 Some of the channels are blocked and some are available

Scenario: CR_example_partially_available_channel_

This is a typical example. In such a scenario, the detection threshold is taken to a value of -80 dB (flat over the frequency range). This mean that when considering the sRSS of Figure 27, for some of the events, the sRSS will be above that threshold and therefore some WSDs will be considered as off (which explains the -1000 dBm value in Figure 28 (b)) and the WSD frequencies are randomly distributed.

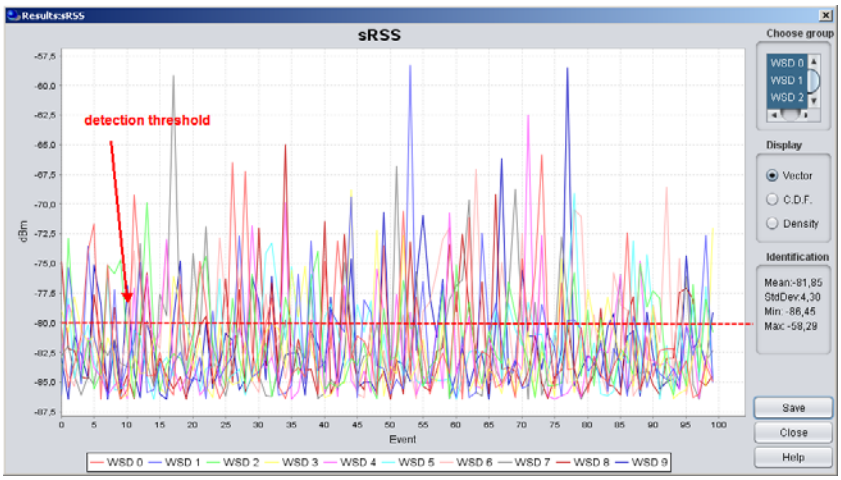
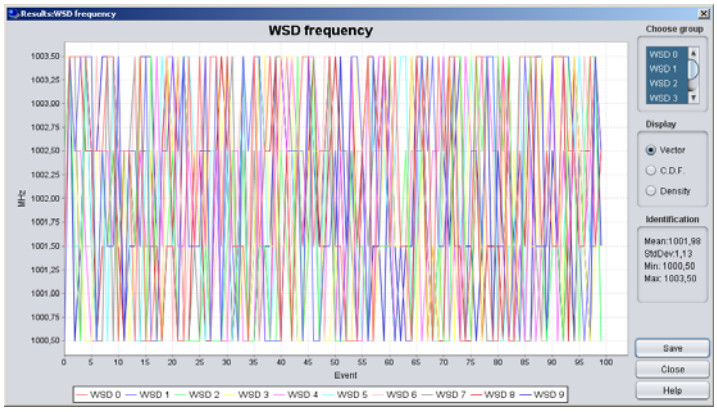
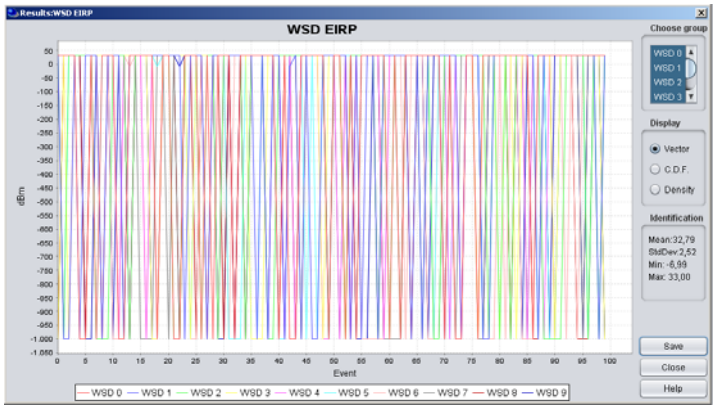


Figure 27: sRSS for 5 WSDs per event



(a) WSD frequency

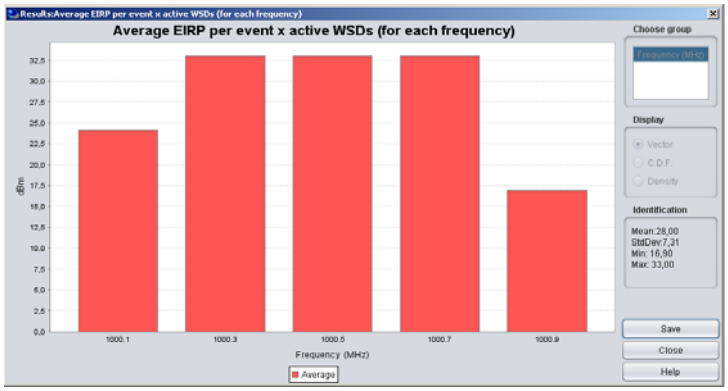


(b) WSD E.I.R.P.

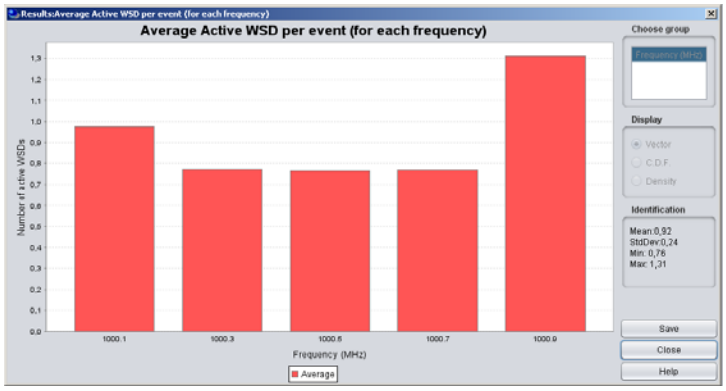
Figure 28: output results of the WSD in (a) frequency and (b) E.I.R.P.

In this case, one can see that all the channels were occupied in Figure 29. The WSDs were allowed to transmit with an E.I.R.P. of 33 dBm in the 3 middle channels (1000.3 MHz to 1000.7 MHz) while for the side channels less power was allowed (i.e. 24 dBm for 1000.1 MHz and 16.89 dBm for 1000.9 MHz).

Figure 29 (b) also indicates that not all the simulated WSDs were active (those having an E.I.R.P. of -1000 dBm), and that per event about only 1 WSD was active.



(a) average E.I.R.P.



(b) average number of active WSDs

Figure 29: output results of the WSD in (a) frequency and (b) E.I.R.P.

For Further Enquiries

Any enquiries to the material in this document as well to the functioning of the SEAMCAT software may be addressed to ECO at:

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Annex 1

How to define the frequency range of the victim device?

The SEAMCAT user can consider numerous ways to define the operating frequency for the victim device. This is presented as below:

Constant:

This return only one channel at a frequency of 900 MHz

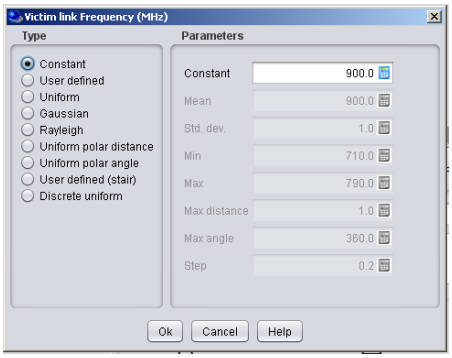

Figure 30: Constant victim frequency

User defined:

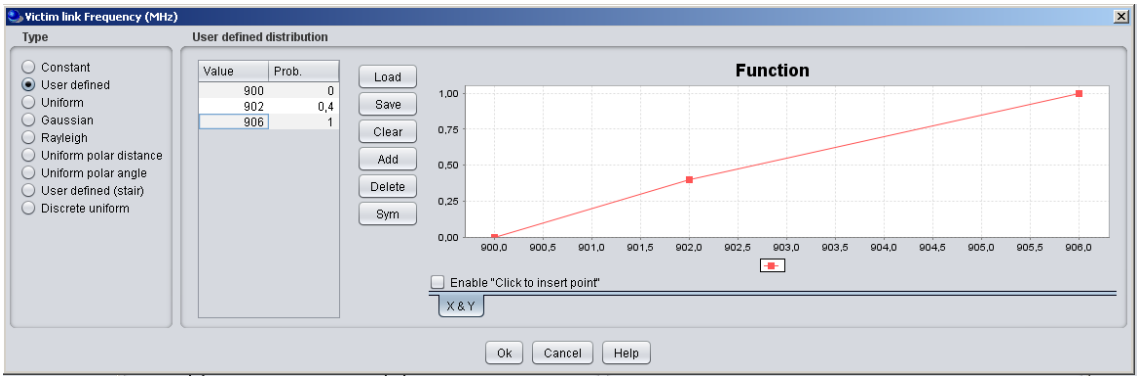

Figure 31: User defined victim frequency

This returns 2 potential WSD channels at 900 and 903.5 MHz with a victim receiver bandwidth of 3.5 MHz while for one snapshot, the victim frequency will operate at 901.031 MHz, for another snapshot it will be 902.636MHz, for another one 905.893 MHz etc…

Gaussian: consistency check exclude this case

Rayleigh: consistency check exclude this case

Uniform polar distance: consistency check exclude this case

Uniform polar angle: consistency check exclude this case

Uniform:

This returns 2 potential WSD channels at 900 and 903.5 MHz with a victim receiver bandwidth of 3.5 MHz. For one snapshot, the frequency of the victim bandwidth will operate at 900.937 MHz, for another snapshot it will be 904.916 MHz, etc…

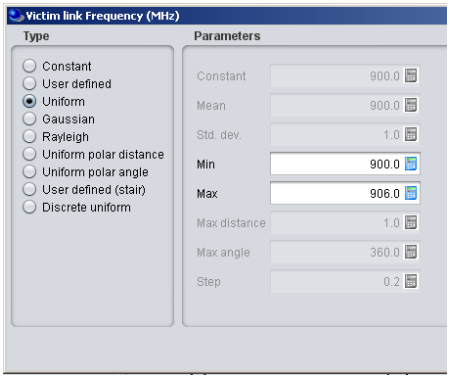

Figure 32: Uniform victim frequency

User defined (stair):

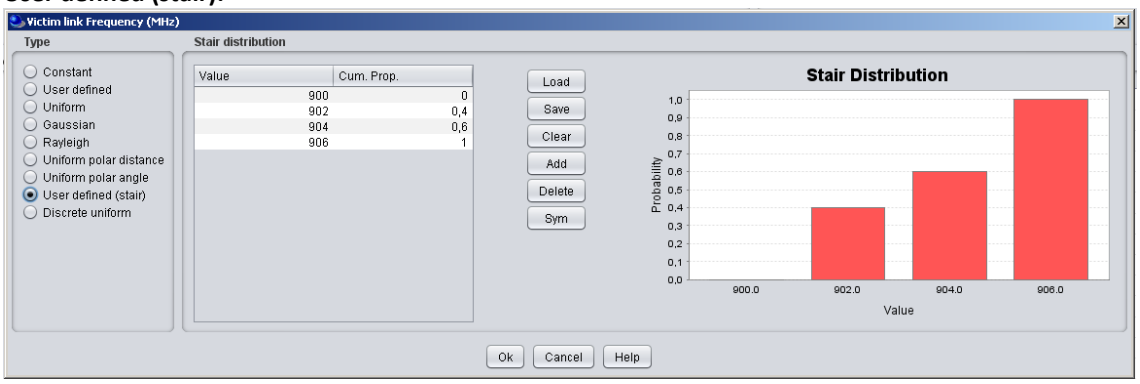

Figure 33: User defined (stair) victim frequency

This returns 4 potential WSD channels at 900, 902, 904 and 906 MHz. For one snapshot, the victim frequency will operate at 904 MHz, for another snapshot it will be 902 MHz, etc…

Discrete Uniform:

This returns 5 potential WSD channels (1000 MHz/200 kHz) at 1000.1, 1000.3, 1000.5, 1000.7 and 1000.9 MHz while for one snapshot, the victim frequency will operate at 1000.1 MHz, for another snapshot it will be 1000.5 MHz, etc…

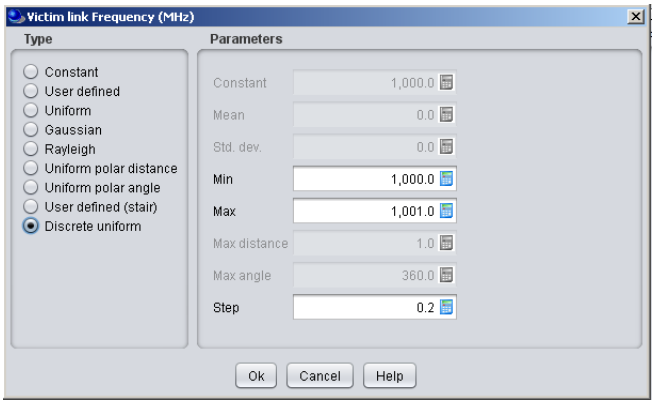

Figure 34: Uniform victim frequency

Annex 2

EGE Input parameters

This annex lists all the input parameters in SEAMCAT user interface useful for setting the Cognitive Radio feature in SEAMCAT. It also explains the use of these parameters in SEAMCAT calculations, where appropriate. The symbols and formatting conventions S means that the input value is in scalar form, D is a distribution and F is a function as a set of corresponding (X, Y) value pairs.

A.2.1 Window Victim link - Wanted Transmitter

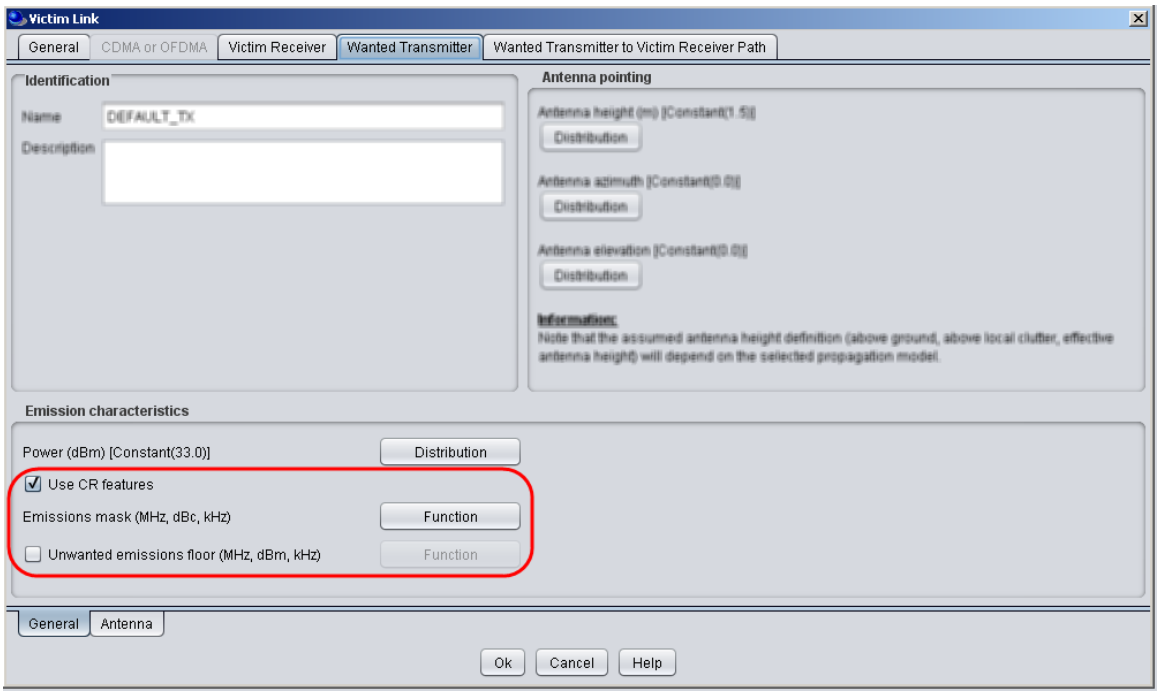

Figure 35: Victim link/Wanted transmitter – CR enabled feature

Page	Description	Sym-bol	Type	Unit	Comments
	Identification dialogue				Unchanged see SEAMCAT Handbook p.113
	Antenna pointing				Unchanged see SEAMCAT Handbook p.113
	Power:		D or S (if constant)	dBm/Vr reception bandwidth	Unchanged see SEAMCAT Handbook p.113
	Use CR feature:		switch		When the CR button is checked then it allows to set the emission characteristics of the Wt (used for the sRSS calculation only)
	Emission mask: Unwanted signal level (Transmitting mask - Wt)		F(MHz)	dBm/reference bandw. (MHz)	Define the mask of the transmitter, in the emission bandwidth and out of the emission bandwidth. Negative values in the relative mask should be chosen in a way that the integration over the emission bandwidth results in the total emitted power, see SEAMCAT Handbook Annex 5 on p. 134. If constant mask, there is no emission outside of the bandwidth.
	Unwanted emissions floor: Noise floor signal level		F(MHz)	dBm/ reference bandw. (MHz)	Define the minimum strength of the unwanted emissions. So the unwanted emissions equal to Max(Pwt + Unwanted emission, Unwanted emissions floor) (see SEAMCAT Handbook Annex 5 on p. 134.)

Table 1: Victim link/Wanted transmitter

A.2.2 Window Interfering link - General

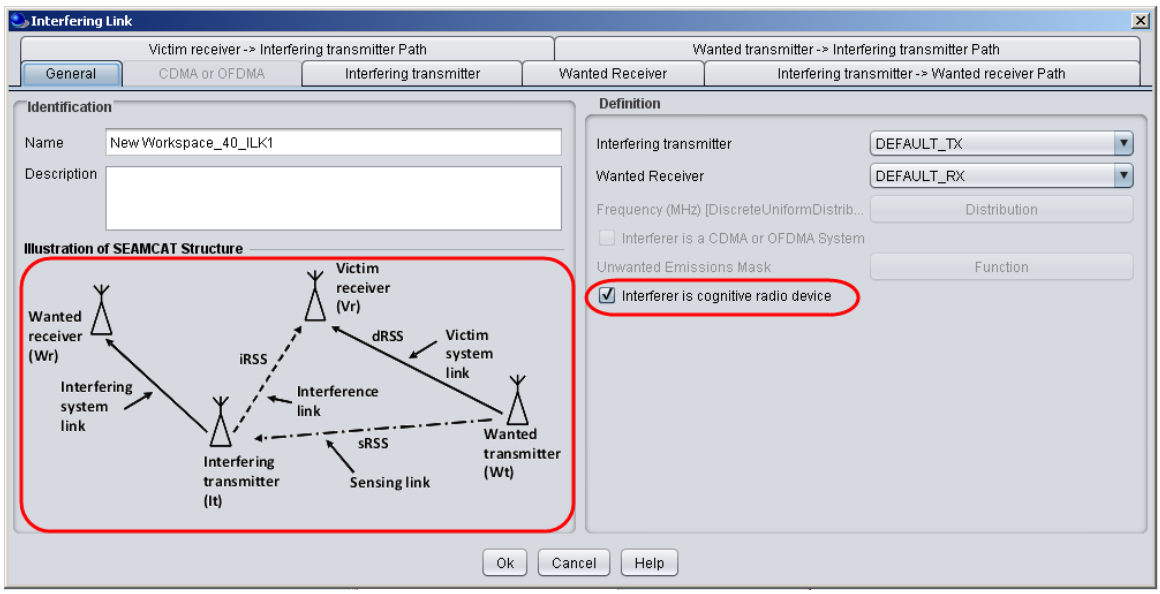

Figure 36: Interfering link/Interfering transmitter – CR enabled feature

page	Description	Symbol	Type	Unit	Comments
	Name: name of the interfering link				Unchanged see SEAMCAT Handbook p.115
	Description: comments on the link				Unchanged see SEAMCAT Handbook p.115
	Illustration of SEAMCAT structure				Display the various link – when CR enabled the sRSS is displayed
	Interfering transmitter:				Unchanged see SEAMCAT Handbook p.115
	Wanted receiver:				Unchanged see SEAMCAT Handbook p.115
	Frequency:				Disabled when CR is enabled
	Interferer is a CDMA System				Disabled when CR is enabled
	CDMA Unwanted emissions mask				Disabled when CR is enabled
	Interferer is cognitive radio device		switch		When the CR button is checked then it allows to set the spectrum sensing characteristics of the It in Wanted transmitter → Interfering transmitter path.

Table 2: Interfering link/general

A.2.3 Window Interfering link – Wanted transmitter → Interfering transmitter path

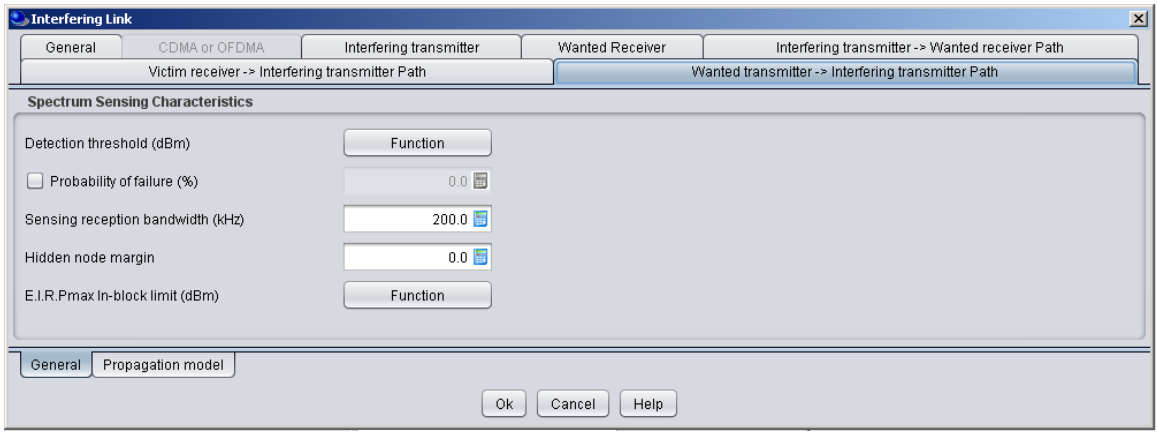

Figure 37: Interfering link/ Wanted transmitter → Interfering transmitter path

page	Description	Sym-bol	Type	Unit	Comments
	Detection threshold:		C or F (offset)	dBm	Define the detection threshold for the spectrum sensing in a offset function. The 0 is refered to the Victim frequency
	Probability of failure:		S	%	Positive value from 0 to 100
	Sensing reception bandwidth		S	kHz	Define the reception bandwidth of the It used in the calculation of the sRSS
	E.I.R.P.max In-block limit		F (offset)	Offset (MHz)/ Mask (dBm)/ Ref.BW (kHz)	Define the E.I.R.Pmax In-block limit to protect the victim system as an offset function where the 0 is refered to the selected interfering frequency. The outcome of the algorithm set the allowed power at the It.

Table 3: Interfering link/ Wanted transmitter → Interfering transmitter path

Annex 3

Output vectors

When the cognitive radio mode is activated, SEAMCAT resturns the output vector shown in Figure 38 and described in Table 4.

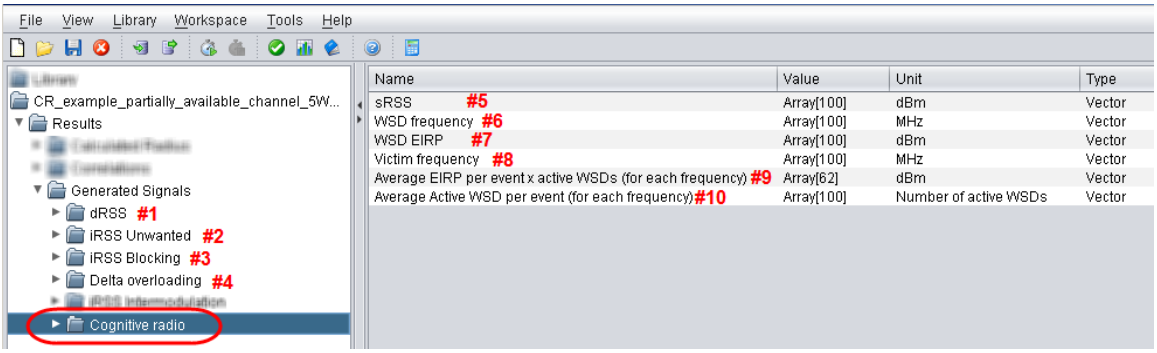

Figure 38: Output vector for the CR

#	item	description
1	dRSS	Unchanged see SEAMCAT Handbook
2	iRSS Unwanted	Unchanged see SEAMCAT Handbook
3	iRSS Blocking	Unchanged see SEAMCAT Handbook
4	Delta overloading	Unchanged see overloading manual http://seamcat.iprojects.dk/wiki/Manual/Algorithms/OverloadingSignals
5	sRSS	sRSS value calculated at the selected WSD frequency (i.e. where the WSD is allowed to transmit) for each of the event
6	WSD frequency	The actual selected frequency at which the WSDs are allowed to transmit as the result of the spectrum sensing algorithm
7	WSD E.I.R.P.	The actual selected E.I.R.P. at which the WSDs are allowed to transmit as the result of the spectrum sensing algorithm
8	Victim frequency	frequency at which the victim device transmits per event
9	Average E.I.R.P. per event x active WSDs (for each frequency)	average E.I.R.P. per event for all the active WSDs transmitting at a certain frequency
10	Average Active WSD per event (for each frequency)	

Table 4: Output results for CR simulation

Annex 4

Spectrum sensing algorithm in SEAMCAT

A.4.1 Basic principle

Assuming ideal case, the basic proposal of a CR is as follows:

if sRSS > Detection threshold -> WSD_{OFF} = no transmission = no interference

if sRSS < Detection threshold -> WSD_{ON} = interference calculation is possible

A.4.2 Overall Algorithm

STEP 1: Identification of the frequencies to be tested.

It is assumed that the frequency of the interfering WSD is dependent on the frequency range defined for the victim. This means that when the CR module is activated, the interfering frequency function dialogue box is deactivated.

M is the number of possible channels that the WSD will operates in.

One can consider following possible ways to define operating frequency for the victim device:

Victim frequency = constant

- interferer frequency = Victim frequency
- M = 1

victim frequencies are discrete

- the possible WSD frequencies are those defined by the user
- M equals the number of discrete inputs

victim frequencies are distributed between f_{min} and f_{max}

- The possible WSD frequencies are from f_{min}+(M-1)*victim bandwidth until f_{max} (i.e. assuming that f is the center frequency). Note that (f_{min}+(M-1)*victim**)** ≤ f_{max}
- Extract M WSD channels

STEP 2: Assigned the WSD with a frequency

for each events{

Note: the victim operates at a single frequency f_v. Several interferers may be operating in various frequencies

if (dRSS > sensitivity){

for each WSDs {

for channel *m = 1 to M+1*(i.e. over all the WSD channels){

STEP 2.1: Calculate the sRSS

- Calculate the sRSS (considering the unwanted mask of the DTT) at the channel *m*

$$sRSS(f_m) = P_{Wt}(f_m) + G_{Wt \to It} + G_{It \to Wt} + L \quad (1)$$

where :

- P_{Wt}: is the transmit power in dBm from the Wt. The bandwidth of the sensing device (It) should be considered in the calculation. Note: The emission bandwidth of the Wt may be different from the It receiving bandwidth, therefore when the sRSS is to be calculated, a bandwidth correction factor is needed. P_{Wt} is subject to power control (p.162 of

SEAMCAT Handbook). The emission spectrum mask of the Wt is provided in order to calculate P_{Wt} at frequency f_m.

- f_m : is the frequency of the WSD.
- $G_{Wt \to It}$: is the antenna gain in dBi of the Wt, in the Wt to It direction
- $G_{It \to Wt}$: is the antenna gain in dBi of the It in the It to Wt direction
- L: is the path loss in dB between the It and the Wt.

(i.e. WSD at f_m and victim at fv) (see eq. 1)

STEP 2.2: Identification of "available" channels

- Detect if a WSD is allowed to transmit (i.e. compare to threshold) (see Section A.4.1)
- Store the channels that are accessible as vector *available_channel*
- Store the channels that are not accessible as vector *non_available_channel*

}

STEP 3: Probability of Failure (if activated)

- Failure status (either TRUE or FALSE) of this WSD is extracted as an event from a distribution. i.e. depending of the $p_{failure}$
- If this WSD has failure = TRUE, then it means that it will transmit in the victim frequency without power constraint
- Update the vectors *available_channel* and *non_available_channel* so that *non_available channel= 0* and *available_channel=1* and is the victim frequency.
- If this WSD has failure = FALSE, proceed without changing the vectors *available_channel* and *non_available_channel*

STEP 4: Select an available channel / determination of the WSD channel

if (*non_available_channel* < 1) (i.e. all are available){

- No frequency is blocked, the max E.I.R.P. of the WSD is considered (i.e. E.I.R.P. deduced from the Tx and antenna gain of the WSD which are inputs to SEAMCAT.) (eq.4)
- The WSD is placed randomly among the *available_channel*

}

else (i.e. one or more channels are blocked (i.e. non-available)){

if (all channels are blocked){

try another WSD → **back to STEP 2.1** *and store the number of inactive WSD*

}

else (not all the channels are blocked){

if (single frequency case) (i.e. frequency = constant){

No frequency is blocked, the max e.i.r.p of the WSD is considered (i.e. e.i.r.p deduced from the Tx and antenna gain of the WSD which are inputs to SEAMCAT.) (eq.4)

}

else {

Step 4.1: Apply the Table of Constraints

For each of the *non_available_channel,* read the associated predefined table (see Table 5) for which the "co-channel" row is synchronised to the non-available channel. Create a new e.i.r.p Table with the dimension (number of rows: number of *non_available_channel*, number of columns: number of *available_channel*). See Annex 5 for an illustration of the process.

for each of the *available_channel*{

- Extract the lowest e.i.r.p from the table. This gives the vector (available channel, e.i.r.p).

Step 4.2: Determination of the WSD channel /e.i.r.p

- From this vector extract the couple (fi, "max e.i.r.p") the vector (available channel, e.i.r.p)
- if several channels are associated with the same "max e.i.r.p" , the WSD is placed randomly among the channels.

}

}

}

}

} (end of the WSD loop)

Note: Now the active WSDs are assigned a frequency and a E.I.R.P.$_{max}$.

STEP 5: Cumulate the frequency/ e.i.r.p of all the active WSDs for each event into a single vector.

Note: The below calculation is as normal to SEAMCAT

for each active WSDs {

Extract the *Tx power* = e.i.r.p $_{max}$ - $G_{maxIt \rightarrow Vr}$ (2)

Calculate iRSS$_{unwanted}$ (i.e. victim at f_v)(see eq. 5) (see Section A.4.4)

Calculate iRSS$_{blocking}$ (i.e. victim at f_v)(see eq. 6) (see Section A.4.4)

Calculate iRSS$_{overlaoding}$ from the interfering WSD to the at the DTT victim receiver frequency.

}

Calculate the $iRSS_{comp}^{unwanted} = \sum_{i=1}^{numberOfActiveWSD} iRSS_i^{unwanted}$

Calculate the $iRSS_{comp}^{blocking} = \sum_{i=1}^{numberOfActiveWSD} iRSS_i^{blocking}$

Note: If none of the WSDs are active iRSS$_{comp}$ = -1000 dB (by default) to allow the interference calculation.

}

else{

Skip this event

}

}

STEP 6: Calculate the Interference

A.4.3 Probability of failure

This feature is input selectable (by default, it is de-activated).The probability of failure may account for the failure in selecting wrongly a *non_available* channel for one event.

This means that when a failure appears, a channel which was initially selected as occupied by a victim DTT becomes "wrongly" available for the WSD to transmit. This results in a "conflict" situation.

For instance with a defined $p_{failure}$, that means that for *x* total of WSD (initial input to SEAMCAT) there is $x*p_{failure}$ WSDs which will transmit in the victim frequency without power constraint. $p_{failure}$ is an input parameter.

A.4.4 Adjacent channel scenario

In the case where the WSDs are not allowed to transmit in the same operating frequency as for the victim DTT device, the WSDs can decide to transmit in the adjacent bands or channels. This scenario is illustrated in Figure 39 In this example the WSDs have sensed that in the channel 6 there is a victim system (here a DTT), therefore the WSDs will choose other channels to transmit.

The maximum permitted in-block and out-of-block E.I.R.P. of autonomous CRs would be specified as a function of the guard band with respect to DTT channels used in the local proximity of the CR. The available guard band would be identified by comparison of the detected DTT signal powers against a fixed detection threshold. [SE43(10)19]

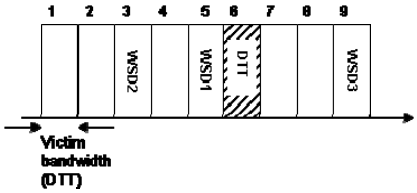

Figure 39: Illustration of WSD1 detecting a victim device in channel 6 and as a consequence decides to operate in channel 3 which is available.

The purpose of the SEAMCAT simulation is to investigate the level of interference created by WSDs to the DTT victim device. Therefore the $iRSS_{unwanted}$ and $iRSS_{blocking}$ for a WSD will be computed.

As a reminder, the E.I.R.P. (Equivalent isotropically radiated power) is defined as:

$$E.I.R.P._{max} = P_{It} - L_c + G_{maxIt \rightarrow Vr} \quad (4)$$

where L_c is the cable loss in dB. We will neglect L_c.

Extract the $Tx\ power = E.I.R.P._{max} - G_{maxIt \rightarrow Vr}$ from **Step 2.5** of the algorithm in section A.4.2.

Calculate the $iRSS_{unwanted}$ from the WSD to the victim DTT device such that:

$$iRSS_{uwanted} = Tx\ power + Emissions\ mask(/unwanted\_emission\_floor) + G_{It \rightarrow Vr} + G_{Vr \rightarrow It} + L_{Vr \rightarrow It} \quad (5)$$

Calculate the $iRSS_{blocking}$ from the WSD to the victim DTT device such that:

$$iRSS_{blocking} = Tx\ power + G_{It \rightarrow Vr} + G_{Vr \rightarrow It} + L_{Vr \rightarrow It} \quad (6)$$

Note: Eq.5 and 6 are unchanged from the "normal" SEAMCAT calculation.

As a result, the interference calculation can be performed on the summation of the $iRSS_{unwanted}$ per channel and $iRSS_{blocking}$ per channel in the case where there are multiple active WSDs per channel.

The In-block input values (dBm), is defined in Table 5 (see Figure 9 for the SEAMCAT interface).

DTT in use at	In-block CR $E.I.R.P._{max}$ limit (dBm)
co-channel	-∞
$n \pm 1$	-12.8
$n \pm 2$	3.2
$n \pm 3$	11.2
$n \pm 4$	16.2
$n \pm 5$	20.2
$n - 6$	16.2
$n + 6$	21.2
$n \pm 7$	22.2
$n \pm 8$	23.2

$n - 9$	4.2
$n + 9$	23.2
$n \pm 10$	24.2
$> n \pm 11$	25.2

Table 5: Example of In-block CR emission limits as a function of guard band with respect to serviced DTT channels as discussed in SE43 (source SE43(10)18).

Annex 5

Determination of the E.I.R.Pmax in-block limit

The following presents the results of the SEAMCAT logfile, when the E.I.R.Pmax in-block limit is to be determined. For this example the following E.I.R.P_{max} in-block limit is set in SEAMCAT

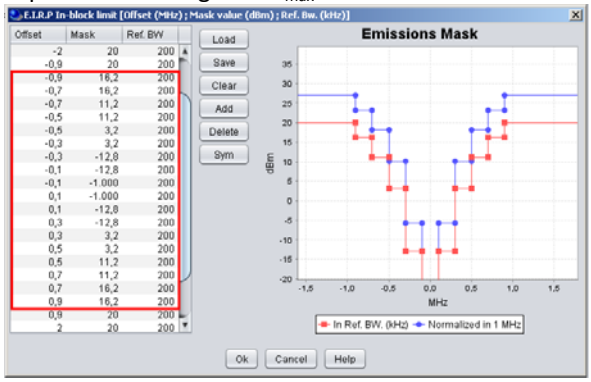

Figure 40: E.I.R.P_{max} in-block limit

The following log file is extracted and it shows the channel availability for one event and for one WSD (It no.1, WSD no. 0). In this case, this WSD would be allowed to transmit at 1000.1 and 1000.3 MHz, but it is not allowed to transmit in the 1000.5, 1000.7 and 1000.9 MHz. The Victim is placed at 1000.9 MHz.

```
(EGE.java:2048[simulateInterference]) - IT is Cognitive Radio (IT no. 1, WSD no. 0)
(EGE.java:2055[simulateInterference]) - There are 5 potential WSD channels
(VictimSystemLink.java:1146[wtUnwantedEmissions]) - Wanted Transmitter Frequency = 1000,900000
(VictimSystemLink.java:1147[wtUnwantedEmissions]) - It Receiver Frequency = 1000,100000
(VictimSystemLink.java:1148[wtUnwantedEmissions]) - It Receiver Bandwith = 0,200000
(VictimSystemLink.java:1149[wtUnwantedEmissions]) - Relative Unwanted Emission = .integrate((ItFreq - WtFreq), ItBandwith) = -106,989700 dBc
(SensingInterference.java:192[powerCalculation]) - Wanted Transmitter Tx Power trial = 33,000000
(SensingInterference.java:193[powerCalculation]) - Absolute Unwanted Emission at WT = wtPower + ReluWanted + wtPower Gain = -73,989700
(SensingInterference.java:221[calculatePathLoss]) - <org.seamcat.propagation.FreeSpaceModel> 111.5077028034609 = evaluate(1000.1,8.9813519000
(SensingInterference.java:60[getSRSS]) - Calculating sRSS -73,989700 + 0,000000 -111,507703 + 0,000000 + 0,000000 = -185,497403
(EGE.java:2073[simulateInterference]) - Evaluating sRSS<detectionThreshold for frequency 1000,100000 MHz = (-185,497403<-100,000000)
(EGE.java:2074[simulateInterference]) - sRSS < detectionThreshold = TRUE  WSD allowed to transmit in the 1000.1 MHz
(VictimSystemLink.java:1146[wtUnwantedEmissions]) - Wanted Transmitter Frequency = 1000,900000
(VictimSystemLink.java:1147[wtUnwantedEmissions]) - It Receiver Frequency = 1000,300000
(VictimSystemLink.java:1148[wtUnwantedEmissions]) - It Receiver Bandwith = 0,200000
(VictimSystemLink.java:1149[wtUnwantedEmissions]) - Relative Unwanted Emission = .integrate((ItFreq - WtFreq), ItBandwith) = -43,523289 dBc
(SensingInterference.java:192[powerCalculation]) - Wanted Transmitter Tx Power trial = 33,000000
(SensingInterference.java:193[powerCalculation]) - Absolute Unwanted Emission at WT = wtPower + ReluWanted + wtPower Gain = -10,523289
(SensingInterference.java:221[calculatePathLoss]) - <org.seamcat.propagation.FreeSpaceModel> 111.50943963402818 = evaluate(1000.3000000000001,
(SensingInterference.java:60[getSRSS]) - Calculating sRSS -10,523289 + 0,000000 -111,509440 + 0,000000 + 0,000000 = -122,032728
(EGE.java:2073[simulateInterference]) - Evaluating sRSS<detectionThreshold for frequency 1000,300000 MHz = (-122,032728<-100,000000)
(EGE.java:2074[simulateInterference]) - sRSS < detectionThreshold = TRUE  WSD allowed to transmit in the 1000.3 MHz
(VictimSystemLink.java:1146[wtUnwantedEmissions]) - Wanted Transmitter Frequency = 1000,900000
(VictimSystemLink.java:1147[wtUnwantedEmissions]) - It Receiver Frequency = 1000,500000
(VictimSystemLink.java:1148[wtUnwantedEmissions]) - It Receiver Bandwith = 0,200000
(VictimSystemLink.java:1149[wtUnwantedEmissions]) - Relative Unwanted Emission = .integrate((ItFreq - WtFreq), ItBandwith) = -6,989700 dBc
(SensingInterference.java:192[powerCalculation]) - Wanted Transmitter Tx Power trial = 33,000000
(SensingInterference.java:193[powerCalculation]) - Absolute Unwanted Emission at WT = wtPower + ReluWanted + wtPower Gain = 26,010300
(SensingInterference.java:221[calculatePathLoss]) - <org.seamcat.propagation.FreeSpaceModel> 111.51117611736825 = evaluate(1000.5000000000001,
(SensingInterference.java:60[getSRSS]) - Calculating sRSS 26,010300 + 0,000000 -111,511176 + 0,000000 + 0,000000 = -85,500876
(EGE.java:2073[simulateInterference]) - Evaluating sRSS<detectionThreshold for frequency 1000,500000 MHz = (-85,500876<-100,000000)
(EGE.java:2074[simulateInterference]) - sRSS < detectionThreshold = FALSE
(VictimSystemLink.java:1146[wtUnwantedEmissions]) - Wanted Transmitter Frequency = 1000,900000
(VictimSystemLink.java:1147[wtUnwantedEmissions]) - It Receiver Frequency = 1000,700000
(VictimSystemLink.java:1148[wtUnwantedEmissions]) - It Receiver Bandwith = 0,200000
(VictimSystemLink.java:1149[wtUnwantedEmissions]) - Relative Unwanted Emission = .integrate((ItFreq - WtFreq), ItBandwith) = -6,989700 dBc
(SensingInterference.java:192[powerCalculation]) - Wanted Transmitter Tx Power trial = 33,000000
(SensingInterference.java:193[powerCalculation]) - Absolute Unwanted Emission at WT = wtPower + ReluWanted + wtPower Gain = 26,010300
(SensingInterference.java:221[calculatePathLoss]) - <org.seamcat.propagation.FreeSpaceModel> 111.5129122536199 = evaluate(1000.7000000000002,
(SensingInterference.java:60[getSRSS]) - Calculating sRSS 26,010300 + 0,000000 -111,512912 + 0,000000 + 0,000000 = -85,502612
(EGE.java:2073[simulateInterference]) - Evaluating sRSS<detectionThreshold for frequency 1000,700000 MHz = (-85,502612<-100,000000)
(EGE.java:2074[simulateInterference]) - sRSS < detectionThreshold = FALSE
(VictimSystemLink.java:1146[wtUnwantedEmissions]) - Wanted Transmitter Frequency = 1000,900000
(VictimSystemLink.java:1147[wtUnwantedEmissions]) - It Receiver Frequency = 1000,900000
(VictimSystemLink.java:1148[wtUnwantedEmissions]) - It Receiver Bandwith = 0,200000
(VictimSystemLink.java:1149[wtUnwantedEmissions]) - Relative Unwanted Emission = .integrate((ItFreq - WtFreq), ItBandwith) = -6,989700 dBc
(SensingInterference.java:192[powerCalculation]) - Wanted Transmitter Tx Power trial = 33,000000
(SensingInterference.java:193[powerCalculation]) - Absolute Unwanted Emission at WT = wtPower + ReluWanted + wtPower Gain = 26,010300
(SensingInterference.java:221[calculatePathLoss]) - <org.seamcat.propagation.FreeSpaceModel> 111.51464804292186 = evaluate(1000.9000000000002,
(SensingInterference.java:60[getSRSS]) - Calculating sRSS 26,010300 + 0,000000 -111,514648 + 0,000000 + 0,000000 = -85,504348
(EGE.java:2073[simulateInterference]) - Evaluating sRSS<detectionThreshold for frequency 1000,900000 MHz = (-85,504348<-100,000000)
(EGE.java:2074[simulateInterference]) - sRSS < detectionThreshold = FALSE
(EGE.java:2081[simulateInterference]) - There are 2 available WSD channels
(EGE.java:2089[simulateInterference]) - Sensing failure feature is DISABLED
(EGE.java:2140[simulateInterference]) - Min EIRP for 1000,100000 MHz is 3,200000 dBm   2 choices
(EGE.java:2140[simulateInterference]) - Min EIRP for 1000,300000 MHz is -12,800000 dBm
(EGE.java:2179[simulateInterference]) - Selected EIRP is 3,200000 dBm and freq is 1000,100000  selection of the frequency and EIRP for theWSD
```

Figure 41: Extract of the logfile

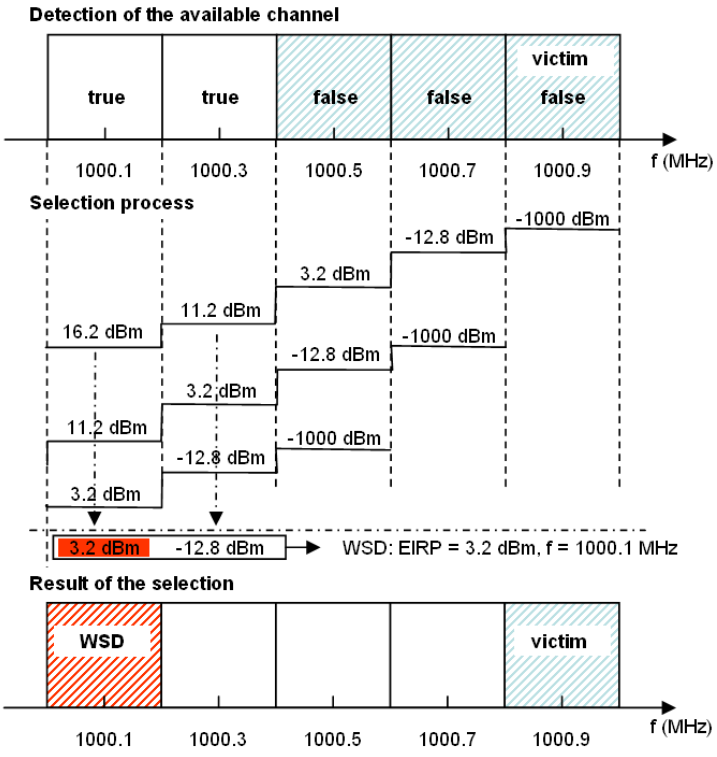

Figure 42: Illustration of the Selection process

Annex 6

Warning message

In case the user selects the wrong distribution for the frequency at the victim link the following warning message will pop-up

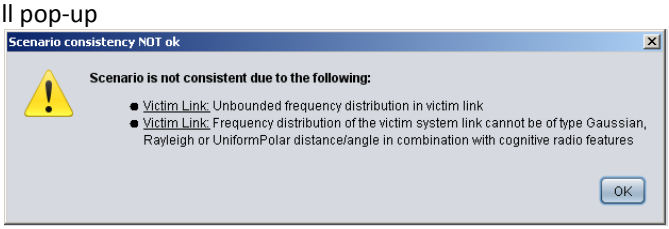
Scenario consistency NOT ok
Scenario is not consistent due to the following:
Victim Link: Unbounded frequency distribution in victim link
Victim Link: Frequency distribution of the victim system link cannot be of type Gaussian, Rayleigh or UniformPolar distance/angle in combination with cognitive radio features
OK

Figure 43: Victim frequency distribution consistency check

If the detection threshold (as a function only) or the E.I.R.P.-in-block limit have their frequency boundaries smaller that the range of the operating victim frequency, the following warning message appears where the offset range is indicated.

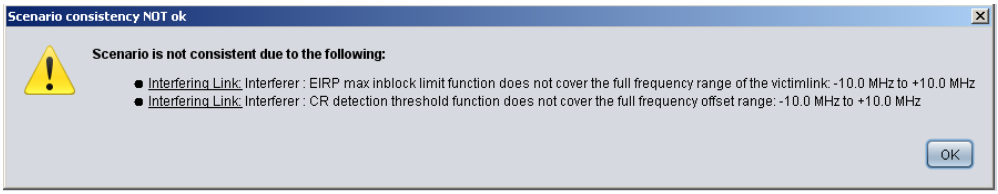
Scenario consistency NOT ok
Scenario is not consistent due to the following:
Interfering Link: Interferer : EIRP max inblock limit function does not cover the full frequency range of the victimlink: -10.0 MHz to +10.0 MHz
Interfering Link: Interferer : CR detection threshold function does not cover the full frequency offset range: -10.0 MHz to +10.0 MHz
OK

Figure 44: Detection threshold and E.I.R.P. in block limit range definition consistency check

If the user forgets to define the Wt emission mask hence to activate the CR in the victim link, he will get the following consistency check warning:

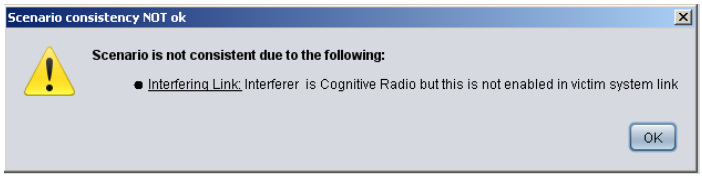
Scenario consistency NOT ok
Scenario is not consistent due to the following:
Interfering Link: Interferer is Cognitive Radio but this is not enabled in victim system link
OK

Figure 45: Consistency check to remind users that the Wt emission mask has to be filled in

If the CDMA or OFDMA module is activated in the victim link it will automatically disable the Wt emission characteristics used for spectrum sensing and the following warning will appear. If the user wants to run CR simulation, he should unselect the CDMA/OFDMA feature from the victim.

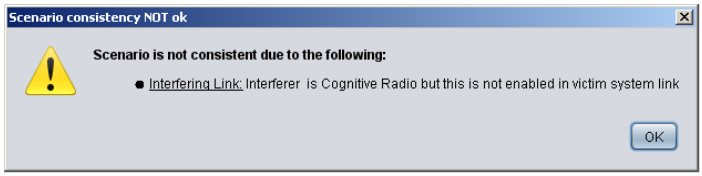
Scenario consistency NOT ok
Scenario is not consistent due to the following:
Interfering Link: Interferer is Cognitive Radio but this is not enabled in victim system link
OK

Figure 46: CDMA/OFDMA usage is not supported for spectrum sensing study

If the unwanted emission mask for the Wt or the It does not cover the whole range of the victim frequency the following warning is displayed.

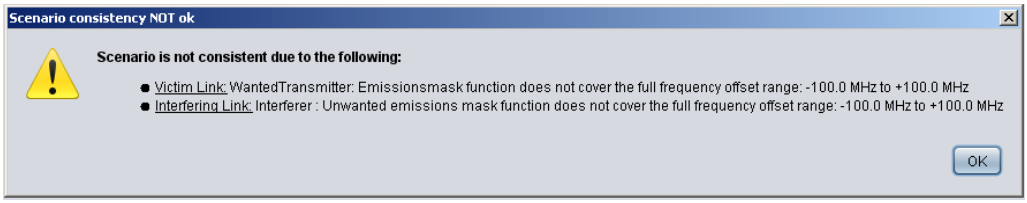
Scenario consistency NOT ok
Scenario is not consistent due to the following:
Victim Link: WantedTransmitter: Emissionsmask function does not cover the full frequency offset range: -100.0 MHz to +100.0 MHz
Interfering Link: Interferer : Unwanted emissions mask function does not cover the full frequency offset range: -100.0 MHz to +100.0 MHz
OK

Figure 47: Unwanted emission mask for the Wt or the It definition range consistency check

The same warning for the blocking response

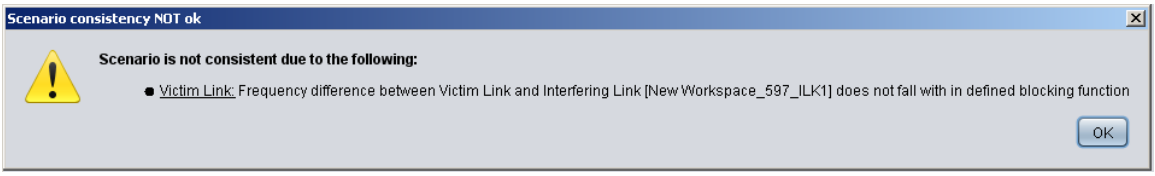
Scenario consistency NOT ok
Scenario is not consistent due to the following:
Victim Link: Frequency difference between Victim Link and Interfering Link [New Workspace_597_ILK1] does not fall with in defined blocking function
OK

Figure 48: Blocking response which range is not defined properly

The reason for this is that the following frequency scenario will happen:

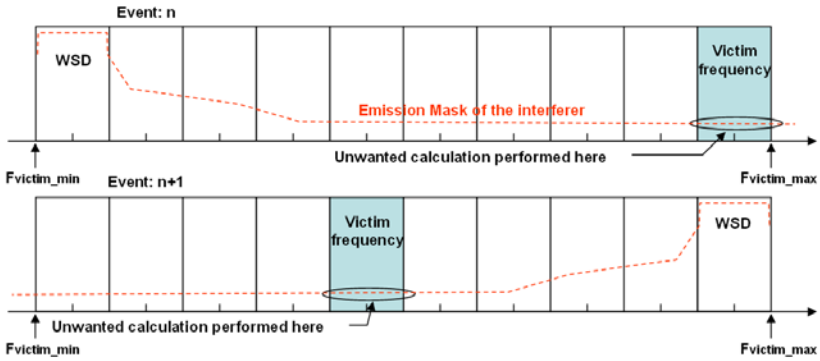

Figure 49: illustration of the emission mask limit

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